Overview of Radioisotope Thermoelectric Generators: Theory, Materials and New Technology

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Jet Propulsion Laboratory
California Institute of Technology

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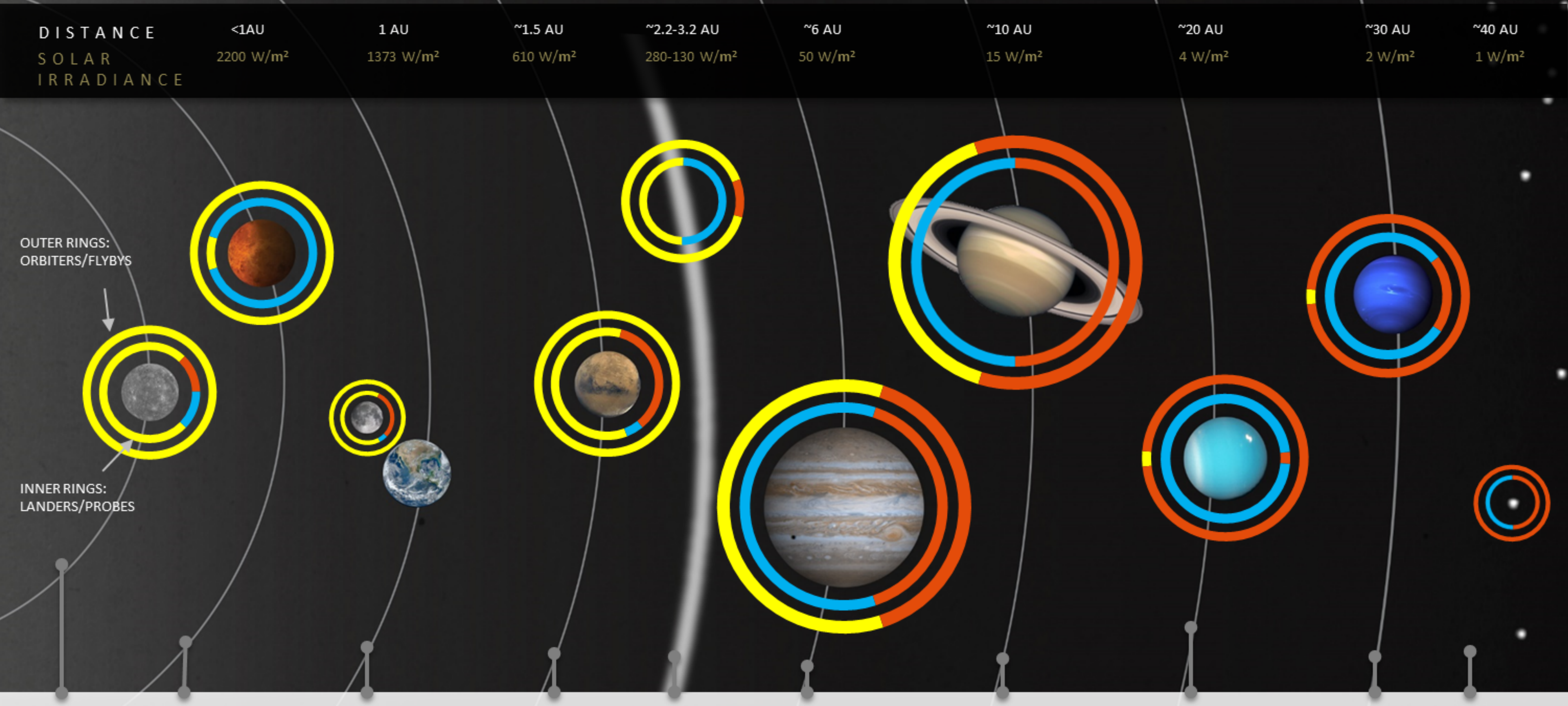


MERCURY

SOLAR
- Orbiters
- Landers
- Rovers

RPS
- Polar Landers
- Long-lived Landers

BATTERIES
- Short-lived Landers

VENUS

SOLAR
- Orbiters
- Upper Atmosphere Probes*
- Surface Probes**

RPS
- Current RPS not operable in Venus surface environment

BATTERIES
- Atmospheric probes
- Surface Missions

MOON

SOLAR
- Orbiters
- Landers
- Rovers

RPS
- Polar Landers
- Long-lived Landers

BATTERIES
- Short-lived Landers

MARS

SOLAR
- Orbiters
- Landers
- Rovers

RPS
- Long-lived Polar Lander
- Long-lived, high capability rovers

BATTERIES
- Short-lived surface missions

ASTEROIDS

SOLAR
- Sample Return
- Flybys/Tours
- Orbiters
- Landers

RPS
- May be necessary for Trojan asteroids

BATTERIES
- Short-lived surface missions

JUPITER

SOLAR
- Orbiters
- Flybys

RPS
- High capability
- orbiters
- Long-lived moon landers

BATTERIES
- Atmospheric Probes
- Short-lived landers

SATURN

SOLAR
- Flyby s/c
- Orbiters

RPS
- High-capability orbiter
- Ring observer
- Titan Montgolfier (MMRTG)
- Long-lived surface mission

BATTERIES
- Atmospheric probes
- Short-lived surface missions

URANUS

SOLAR
Not likely to be practical

RPS
- Orbiters
- Flybys
- Moon landers

BATTERIES
- Atmospheric probes

NEPTUNE

SOLAR
Not likely to be practical

RPS
- Orbiters
- Flybys
- Long-lived Triton Lander

BATTERIES
- Atmospheric probes

KUIPER BELT

SOLAR
Not likely to be practical

RPS
- Orbiters
- Flybys
- Landers

BATTERIES
- Short-Lived landers

*requires technology development for solar cells in corrosive environment
**requires technology development for high temperature

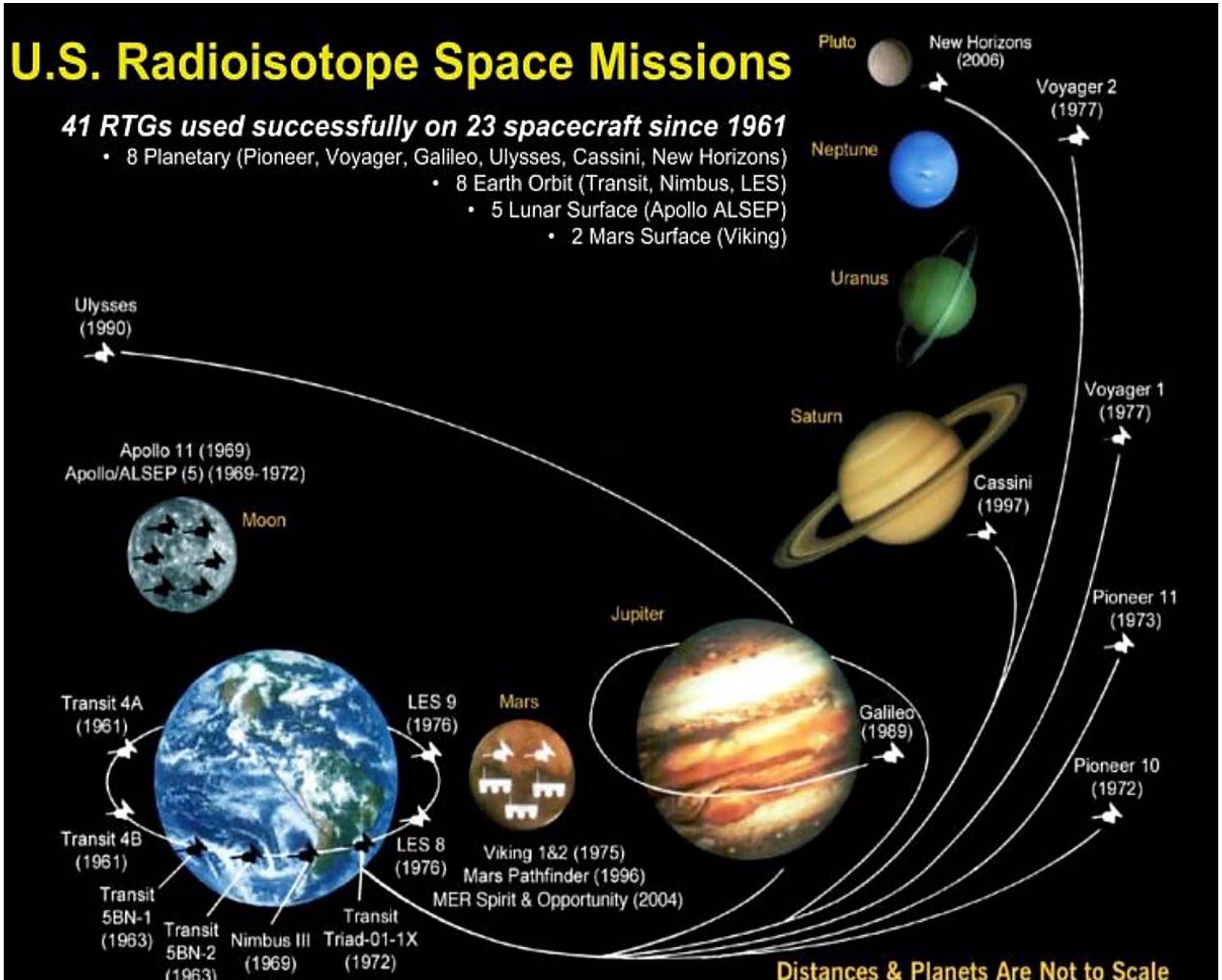
POWER TECHNOLOGIES APPLICABLE TO SOLAR SYSTEM EXPLORATION MISSION CONCEPTS AS OF 2015[(1)]

(1) Notional mission applicability based on expert opinion developed in JPL A-Team study in August, 2015. Updated 2017.

Solar
RPS
Primary Battery

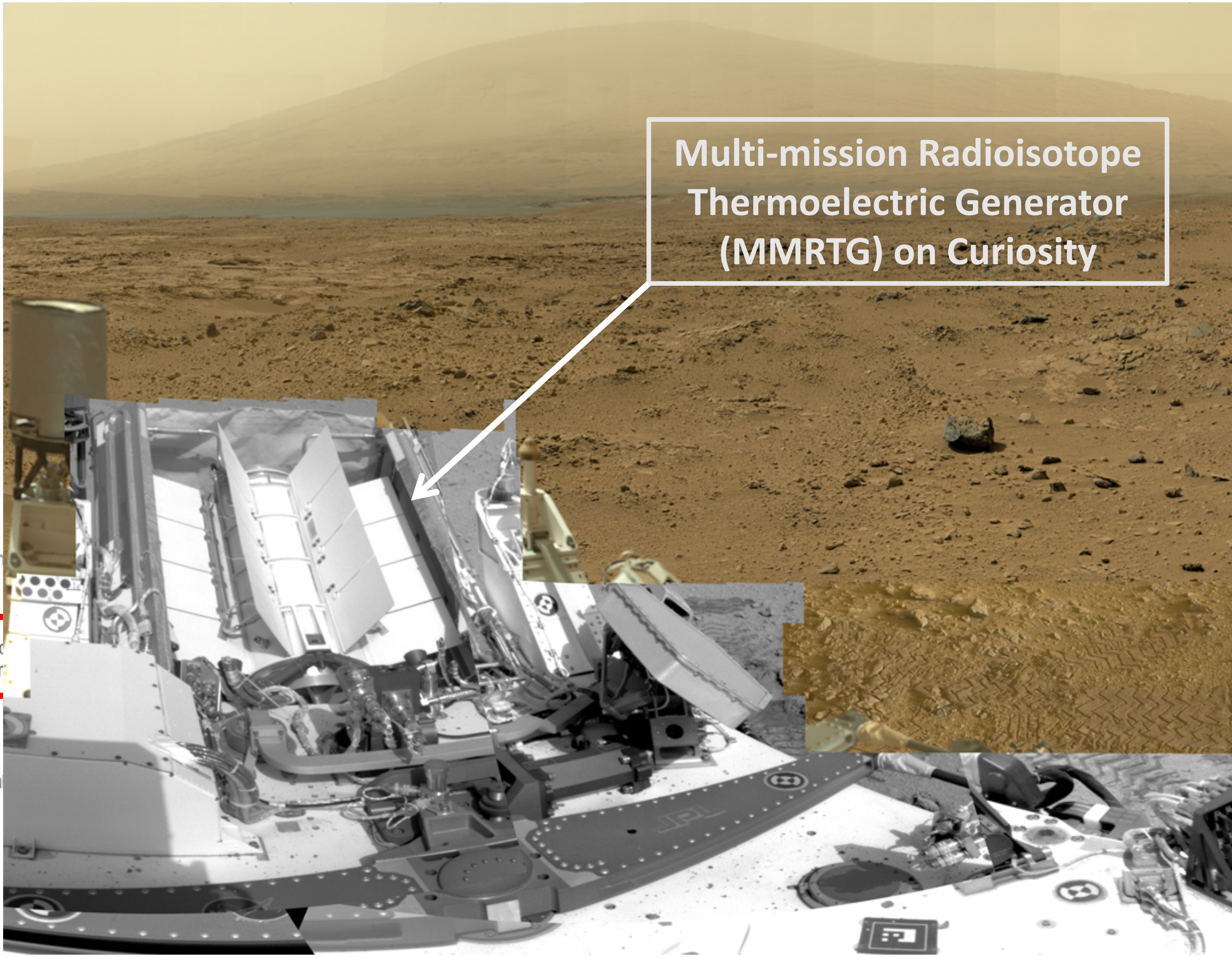
Approximate relative applicability of power technologies to target body missions

RTGs in U.S. missions



Mission name	TE Mater.	Launch year
Transit 4A	PbTe	1961
Transit 4B	PbTe	1962
Apollo 12	PbTe	1969
Triad-01-1x	PbTe	1972
Pioneer 10	PbTe	1972
Pioneer 11	PbTe	1973
Viking 1	PbTe	1975
Viking 2	PbTe	1975
LES 8	Si-Ge	1976
LES 9	Si-Ge	1976
Voyager 1	Si-Ge	1977
Voyager 2	Si-Ge	1977
Galileo	Si-Ge	1989
Ulysses	Si-Ge	1990
Cassini	Si-Ge	1997
New Horizons	Si-Ge	2006
MSL	PbTe	2011

MMRTGs architecture

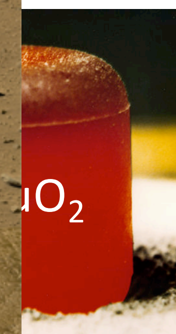


Microth

Thermoelec
Assem

Modu

K

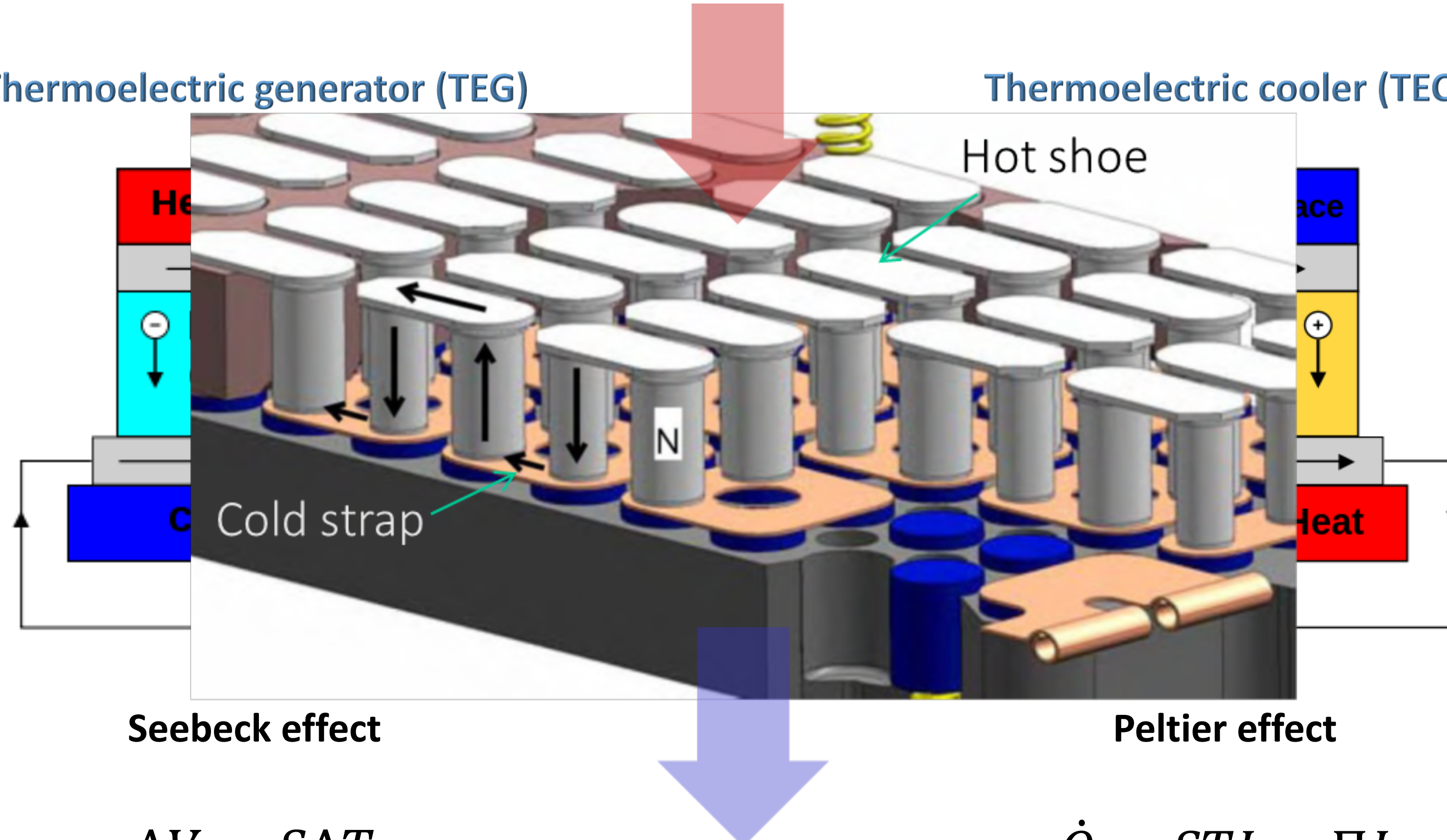


pellets

Thermoelectric conversion

Thermoelectric generator (TEG)

Thermoelectric cooler (TEC)



Seebeck effect

Peltier effect

$$\Delta V = S\Delta T$$

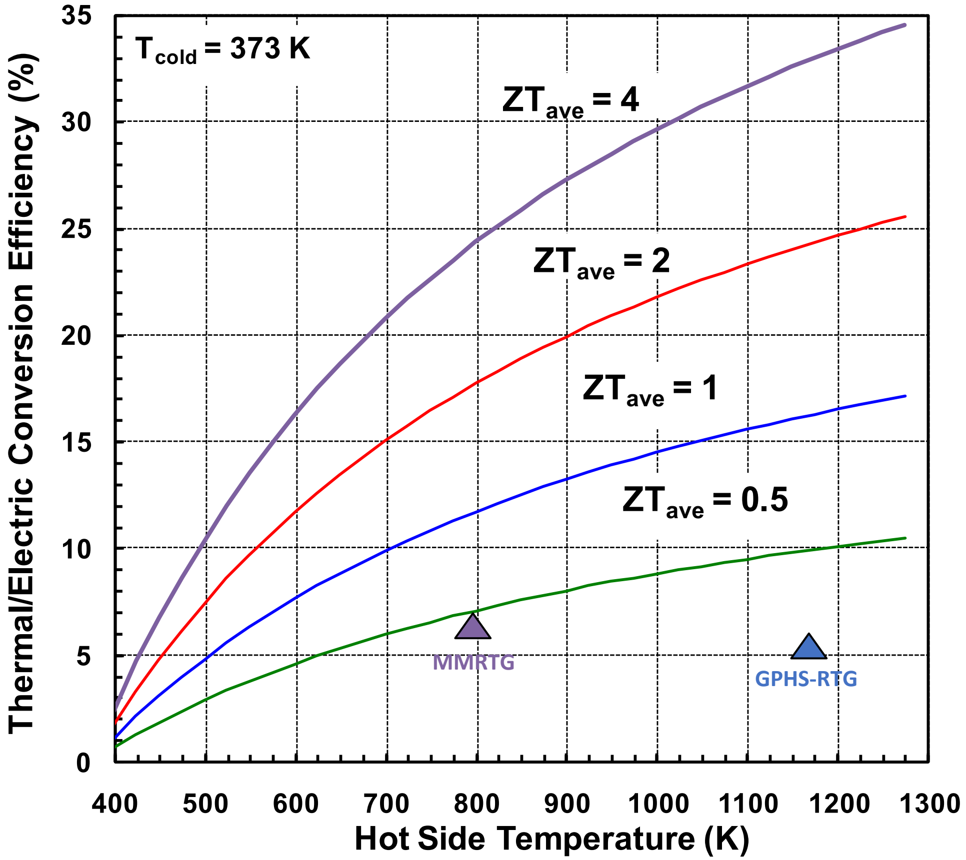
$$\dot{Q} = STI = \Pi I$$

https://en.wikipedia.org/wiki/Thermoelectric_generator, downloaded on 9th March 2017.

Thermoelectric power generation

Carnot — TE Materials

$$\eta_{\max} = \frac{T_{hot} - T_{cold}}{T_{hot}} \frac{\sqrt{1+ZT} - 1}{\sqrt{1+ZT} + \frac{T_{cold}}{T_{hot}}}$$



Power generation

(across 1275 to 300 K)

State-Of-Practice materials:

$ZT_{average}$ ~ 0.5

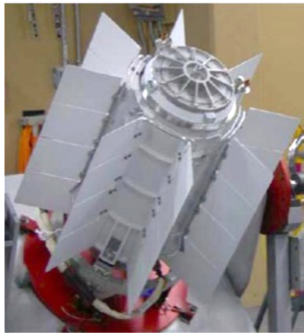
State-Of-the-Art materials:

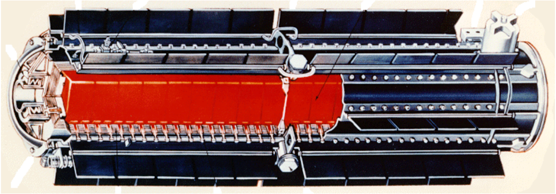
$ZT_{average}$ ~ 1.1

Best SOA materials:

ZT_{peak} ~ 1.5 to 2.0

PbTe/TAGS MMRTG (2008-present)





SiGe GPHS RTG (1980-2006)

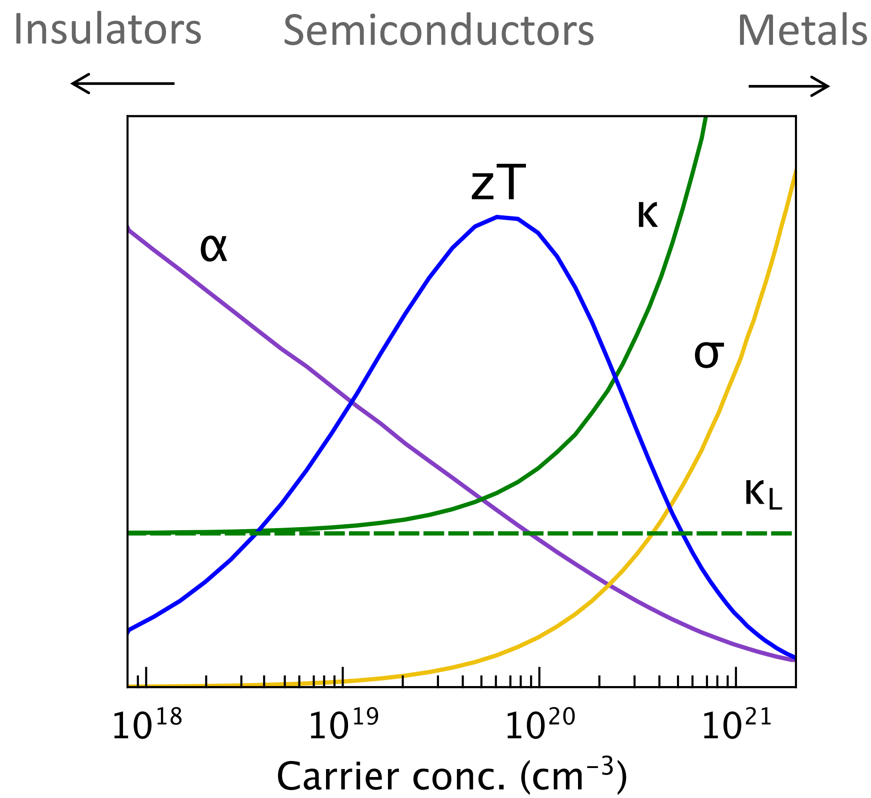
Thermoelectric figure of merit

α = Seebeck coeff. ($\Delta V/\Delta T$)

σ = Electrical conductivity

$$zT = \frac{\alpha^2 \sigma T}{\kappa}$$

κ = thermal conductivity



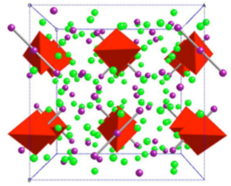
1. Maximize power: $P = V^2 / R$
2. Minimize energy loss to Joule heating
3. Minimize energy loss via heat conductance

Challenge: Decouple the electronic and thermal transport

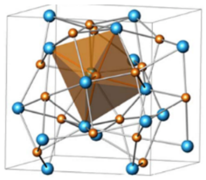
"phonon glass, electron crystal"

Improving zT

- Starting with compounds characterized by ***complex crystal structures*** (inherently low thermal conductivity).

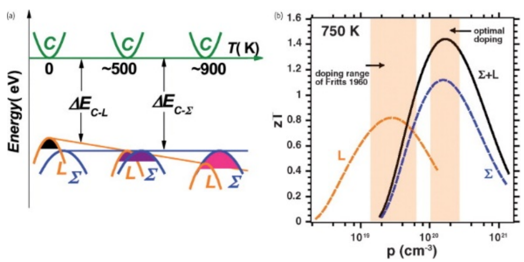


Zintl phases



Th_3P_4

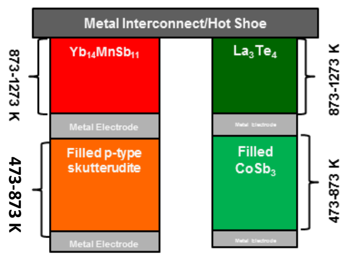
- Manipulation of electronic properties through ***band engineering*** (alloying/doping).



- ***Compositing*** to improve mechanical stability and electronic properties while reducing κ.

- Close coupling between theoretical ***simulations and experimental*** research:
  - Computational work to guide experimental.
  - Semi-empirical modeling to optimize materials systems.

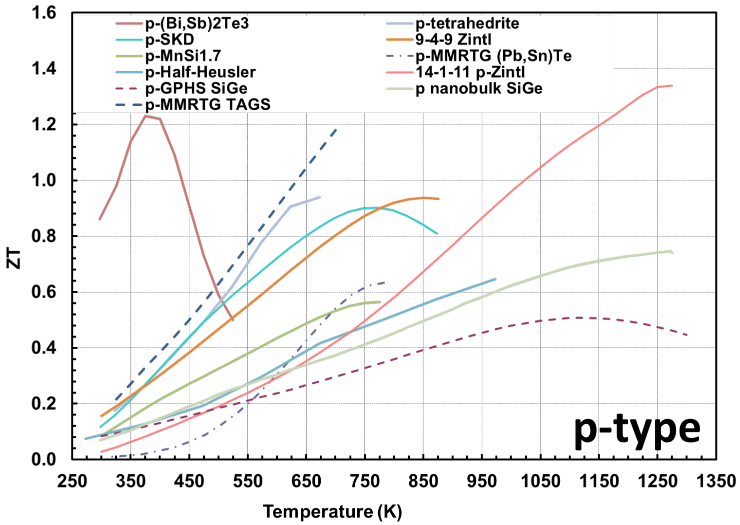
- ***Segmentation***:
  - zT_{avg} improved with segmented legs using materials that have peak zT at different temperatures.

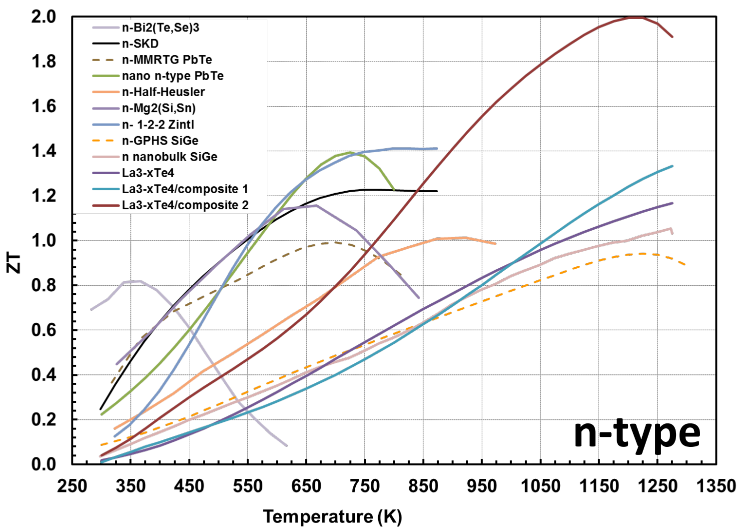


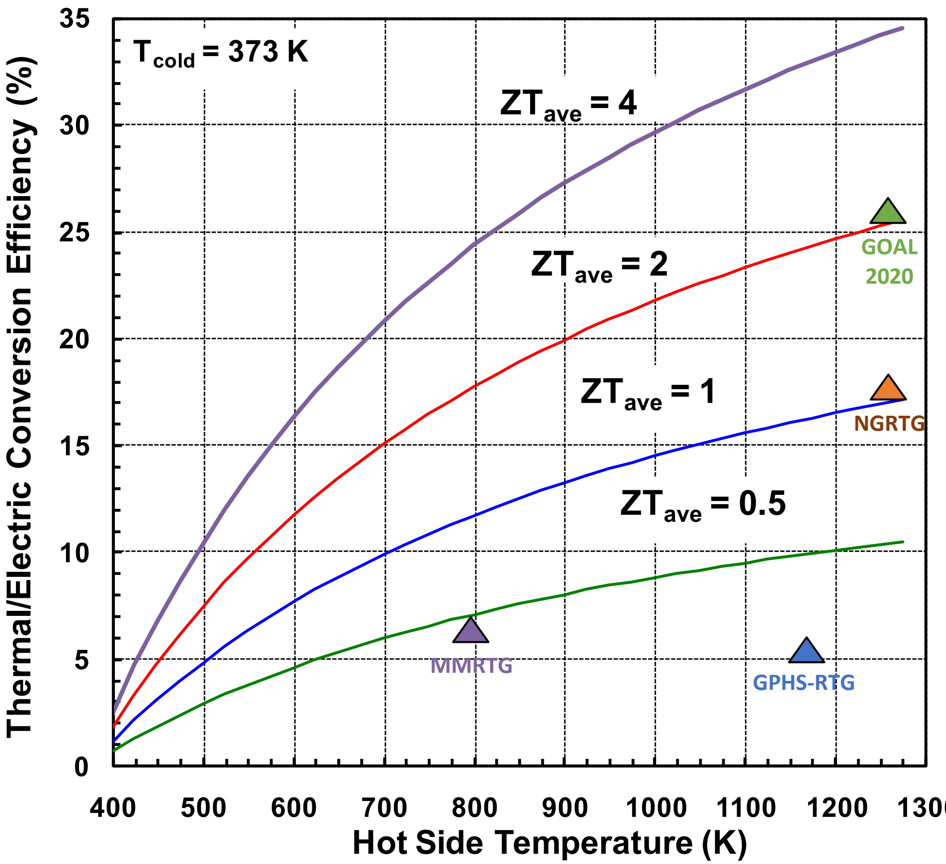
Advanced Segmented Couple
1273-473 K

LaLonde et al., *Mater. Today*, **2011**, 526-532.

Now and the future







- ✓ Large improvements in last 15 years!
- ✓ Better understanding of materials.
- ✓ NASA goal of $\eta > 20\%$ by 2020.

Acknowledgments

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See

- *https://rps.nasa.gov/*
- *https://www.jpl.nasa.gov/*

- **TECT Group, JPL**
- **Power and Sensors Systems Section, JPL**

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